

Electric Field Screening by Pairs in the Presence of Returning Positrons

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Abstract. We solve the one-dimensional Poisson equation along a magnetic field line, both analytically and numerically, for a given current density incorporating effects of returning positrons. We find that the number of returning positrons per one primary electrons should be smaller than unity, and the returning of positrons occurs only in a very short braking distance scale. As a result, for realistic polar cap parameters, the accelerating electric field will not be screened out; thus, the model fails to be self-consistent. A previous belief that pair creation with a pair density higher than the Goldreich-Julian density immediately screens out the electric field is unjustified. We suggest some possibilities to resolve this difficulty.

1. Introduction

High energy pulsed emission from rotation powered pulsars are accounted for by presuming an electric potential drop along a magnetic flux in the magnetosphere, as typically seen in ‘polar cap models’ or ‘outer gap models’. The available potential drop produced by the neutron star is enough for the emission. In particular, for young pulsars acceleration potential is only a small portion of the total electromotive force. Rather important is how we understand localization of the electric field. In some mechanism, the actual charge density deviates from the Goldreich-Julian (GJ) charge density to produce field-aligned electric field. It is sometimes naively assumed that if pairs are created with a density higher than the GJ density, then produced field-aligned electric field is screened out and shut down the accelerator localized in a small region. In this work, we treat such a screening process by pairs and find out conditions to obtain a finite potential drop.

Let us consider a steady model for the field-aligned accelerator which has a finite potential drop with the electric field screened at the both ends. For definite sign of charge, let us assume electrons are accelerated outwards, i.e., the electric field points toward the star. Gamma-rays emitted by the electrons convert into pairs beyond a certain surface called the pair production front (PPF); beyond PPF pairs are assumed to be created continuously in space. A schematic structure is shown in Fig. 1, and the electric potential may be given by, in non-dimensional form,

$$-\frac{d^2\phi}{dx^2} = -\frac{j}{v_1/c} + \frac{B_z}{B} + \bar{\rho}_- + \bar{\rho}_+ \quad (1)$$

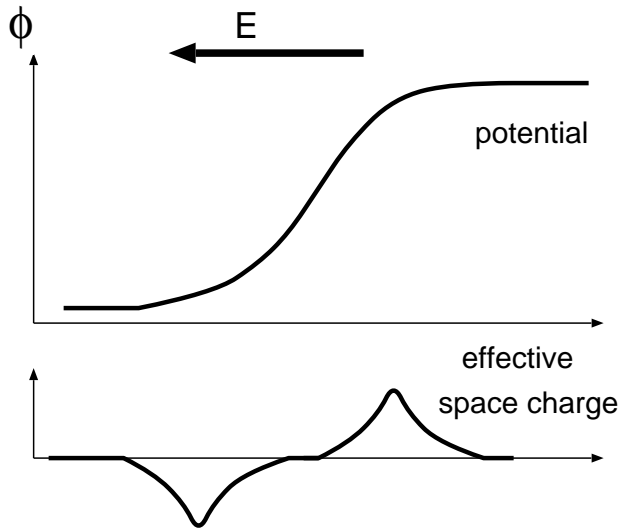


Figure 1. Schematic picture of the field-aligned accelerator

where the first negative term is due to the primary electron beam, the second term is the normalized GJ density, and the last two terms appear due to pairs only beyond PPF.

In the ‘standard’ polar cap model, the negative space charge (cathode) is produced by non-relativistic electrons near the surface (when $v_1 \ll c$). If the length of the acceleration region along field lines is larger than the transverse scale, negative charge appearing on the side wall also contributes. Such an electric field can be screened by two possible reasons; one is when the GJ term (the second term) dominates the primary electronic charge (the first term), and the other is when pairs are created.

In the former case, it is obvious that the primary current should be less than a value, typically of order of GJ value, depending how slowly B_z decreases as compared with B . As is well-known, field lines curving toward the rotation axis, B_z/B term increases and is favorable to the case (Scharlemann, Arons, & Fawley; 1978, Arons, & Scharlemann; 1979). In order to shutdown the potential drop, the current density should be adjusted to be a critical value determined by the field geometry. However, the current density is determined globally, especially, through interaction with the wind zone, so the actual current density is likely to be different from the critical current density. The screening is nothing to do with the pair creation in this case. If pair creation takes place, the strict condition on the current density is slightly relaxed; as will be shown below some of pair positron returns back to the star and left pair electrons behind, which provide negative space charge in the ‘anode region’. Therefore if the actual primary current is *less* than the critical value, i.e., if the region needs negative charge to adjust the GJ (positive) term, then pair plasma helps to adjust the space charge

to close the accelerator. If the situation is opposite, namely, if current density is much higher than the critical value, there is no way to close the accelerating electric field, even in the away curved field lines.

I would like to argue that such super critical current density seems realistic. The critical charge density is more or less GJ. The GJ current is obtained by some sort of dimensional analysis: the current derived from the magnetic moment μ , angular velocity Ω and other physical constants is $I = \mu^2 \Omega^4 / c$. This estimate for the circulating current in the magnetosphere will be correct. However, the GJ current density $B\Omega/2\pi c$ is just I divided by the polar cap area. It is not likely that current density is distributed more or less uniformly over the polar caps, and much likely that it is localized in annular rings or clumps, hinted by radio profiles and also by terrestrial aurora. An expected current density can be by factor of 10 or 100 larger than the GJ current density. If one assume such a super GJ current density, it is certain that strong accelerating electric field appears as shown by Shibata (1997) regardless of the field geometry.

The second case that the screening is due to pairs may be sometimes assumed. Pair polarization is an effect that screens out the electric field. The pair positrons are decelerated to non-relativistic speed soon after their birth, while the pair electrons are accelerated, and as a result of continuity, a positive space charge appears to reduce the electric field. However, some positrons reflected backward to the star by un-screened electric field. In this paper, we calculate the positive space charge produced by pair polarization and obtain the electric field strength which can be screened.

2. Model

We assume one dimensional primary stream along a field line, and pairs, which is created beyond the PPF more or less uniformly. Pair density is parameterized by 'multiplication factor' $M(x)$, by which the primary electronic flux is multiplied to give pair flux at the point x . The Poisson equation for the electric potential and equations of motion and of continuity for electrons and positrons are solved self-consistently for a steady state solution.

3. Results

We obtain the electric field strength which can be screened, given a pair creation rate. It is found that returning of positrons makes the screening difficult seriously, because the pair electrons left behind the returning positrons produce negative space charge in the screening region where the positive space charge is required. As a result, the thickness of the screening is restricted to be as small as the braking distance $\Delta s \approx mc^2/e|E_{\parallel}|$ for which positrons become non-relativistic, where E_{\parallel} is the electric field strength just before the PPF. We confirmed the previous result of Shibata et al. (1998) that the electric field which can be screened by pair polarization is fairly small:

$$\frac{E_{\parallel}^2}{8\pi} < mc^2 \left(\frac{\Omega B}{2\pi ce} \right) \zeta' j \Delta M_{\text{screen}} \quad (2)$$

where ΔM_{screen} is the pair multiplication factor *within* Δs , ζ' is a numerical factor of order of unity.

If the primary current density is of order of the Goldreich-Julian (GJ) value, the required pair multiplication factor per one primary electron is enormously large and cannot be realized in the conventional pair creation models. A previous belief that pair creation with a pair density higher than the GJ density immediately screens out the electric field is unjustified.

Some mechanism to salvage this difficulty should be found. As has been mentioned in §1, the toward curvature provides an effective positive charge, so that the required multiplication factor is considerably reduced. In this case, over-screening by the positive GJ term is canceled by the pair electrons left behind the returning positrons (this is the opposite of pair polarization). Harding & Muslimov (2001) is the case, but the current is restricted to be sub-GJ. In a more likely case with super-GJ current density, toward curvature will not be helpful. In any case, physics in focused field-aligned current, e.g., effects of inhomogeneity across the magnetic field lines, two stream instability in a high current density with unscreened electric field, has yet been properly studied.

Another possible way out is to include frictional forces between various components of charged currents. Since friction on positrons pulls them outwards along with electrons, returning fraction of positrons will be reduced, which will make screening easier. Although there are some ideas for physical processes of friction (two stream instability, production of positroniums and others), it is not clear whether the frictional force can be strong enough to lift positrons and screen the electric field. Study on the frictional interaction under *unscreened* electric field is strongly demanded.

More detailed analysis and results will be published in near future (Shibata, Miyazaki & Takahara 2001).

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